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Energy saving in sugar manufacturing through the integration of environmental friendly new membrane processes for thin juice pre-concentration

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ABSTRACT

In the present work energy savings in clarified thin sugar juice pre-heating and concentration are presented by integrating a new pressure-driven multistage membrane process with multiple-effect evaporator (MEE). The thin sugar juice is concentrated from 15 w% to 50 w% with membrane and from 50 w% to 70 w% in MEE. The new process will not only reduce the energy consumption of thin juice concentration process significantly but will also reduce the requirements of energy and heat transfer area of heat exchangers for pre-heating the thin juice before evaporation by 70%. The existing sugar factories may increase the capacity of their evaporation station through the integration of the new membrane process while new factories to be built will have a smaller sized evaporation station with more energy efficiency and environmentally friendly process performance and with a significantly smaller carbon footprint.

1. Introduction

World sugar production in the year 2009/10 was 158.830 Mt and is expected to reach 170.375 Mt in the year 2010/11 [1]. Sugar manufacturing is one of the most energy intensive processes. Increasing fuel prices and stringent environmental regulations are convincing sugar manufacturers to search for alternative energy efficient and environmentally friendly processes. To improve the economic and environmental performance of the beet sugar industry, Krajnc et al. [2] proposed a zero-waste emission strategy in a case study of a beet sugar factory in Slovenia. In their study they investigated the possible use of waste and by-products from sugar processing to approach zero-waste from beet sugar processing. For utilizing by-products in a useful way, Vaccari et al. [3] proposed the use of pulp and carbonation sludge for the production of paper.

Extensive efforts have been made by the researchers to minimize the energy consumption in sugar manufacturing by one or the other way. The most extensively used approach was retrofitting. A sugar factory retrofit often includes improvements in the factory's energy system comprising power plant, multiple-effect evaporator and process heating equipment [4]. Presently the sugar juice is concentrated by evaporation in MEE which is a very energy intensive process.

Therefore, most of the research work presented in recent years for decreasing the energy consumption in sugar manufacturing has been devoted to the retrofitting of the multiple-effect evaporators and heat exchanger network [5].

By the application of retrofitting techniques and optimization through sophisticated simulation tools the evaporation stations of the sugar factories are extremely efficient in terms of steam and equipment usage. Consequently, there is not much scope for energy optimization by using the present technology of evaporation for concentrating thin sugar juice. Membrane technology has the advantage to remove the water from solution without phase change. Therefore it requires low energy with less thermal damage for concentrating aqueous solutions compared to conventional evaporation.

The potential of membrane technology in the sugar industry has been studied by many researchers but the focus was mainly on sugar juice purification in order to avoid or to decrease the use of lime and multiple purification steps [6,7]. Reverse osmosis (RO) is a type of pressure-driven membrane that has the capability to pass water and reject other dissolved solutes hence concentrates the solution without phase change. The driving force for passing the water/solvent through the membrane is the difference in applied pressure by the pump and the osmotic pressure of the solution at the membrane surface. The technical feasibility of using RO for concentrating various sugar solutions has been demonstrated in

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commercial practise for the application involving lactose concentration from cheese whey in the dairy industry and pre-concentration of fruit juices etc.

Initial investigations for the application of RO in the sugar industry started in the beginning of the 1970s with cellulose-acetate membranes [8,9], but due to temperature limitation of these membranes, the tests were conducted at 20 °C–30 °C, which resulted in very low fluxes and the risk of microbial growth [10]. With the development of thin-film reverse osmosis membranes, it became possible to concentrate thin juice at higher temperature with no risk of microbial contamination and sufficiently higher fluxes. A technical feasibility of reverse osmosis for thin juice pre-concentration has presented by Sandre in 1981 [11]. He demonstrated the attractiveness of reverse osmosis for thin juice concentration from 13 to 30 % with the PA300 RO membrane at high temperatures. The paper clearly shows the benefits and advantages of membrane technology over multiple-effect evaporation including lower costs.

Koekoek et al. [12] tested nanofiltration (NF) spiral wound and tubular modules for the concentration of thin juice and the removal of non-sugars from the thin juice to reduce the load of the non-sugar to the crystallization stage. They presented a 30% reduction in steam consumption by concentrating thin juice up to 22 w% but they also faced severe fouling problem in long term testing. The problem of fouling can be reduced by application of softening process (ion-exchange) which is already adopted by many industries to reduce the fouling in MEE. More recently, Madaeni et al. [13] characterized different commercial reverse osmosis and nanofiltration membranes for thin juice concentration. Madaeni and Zereshki [14,15] reported 33% savings in energy consumption by concentrating thin sugar juice from 15 w% up to 20% by BW30 reverse osmosis membrane. But in their experiment they had to cool the feed from 80 °C to 30 °C as the maximum operating temperature limit of the membrane was 45 °C.

In the present study energy savings in pre-heating the thin juice before evaporation and in concentrating thin juice from 15 w% to 70 w% are shown by the application of a newly developed multistage pressure-driven membrane separation process. The new membrane process is capable to concentrate the thin sugar juice from an initial feed concentration of 15 w% to 50 w% through membranes with moderate transmembrane pressure of 32 bar at 80 °C. This will remove 82 w% of water from the solution without any phase change. The pre-concentrated juice can then be sent to an evaporator for final concentration up to 65–70 w%. The hybrid concentration process of membrane and evaporation can save more than 80% of energy in the concentration step and about 70% reduction in heat and heat transfer area requirements for pre-heating the juice before evaporation.

2. Brief description of sugar manufacturing process

The sugar industry processes sugar cane and sugar beet to manufacture edible sugar. About 40% of the world's sugar production is from beet, and 60% is from cane. The climates of most sugar-producing countries are suitable for growing either beet (in moderately cold areas) or cane (in tropical areas) [16]. A simplified process flow sheet of conventional sugar manufacturing process is shown in Fig. 1.

After arrival at the mill, beets are cleaned through washing with water to remove larger amounts of rocks, trash, and leaves, etc. To improve the extraction operation and to remove the sucrose from the beets, they are sliced into long, thin strips, called cossettes.

The optimum temperature for the extraction of sucrose from sugar beet in the beet sugar industry is about 70 °C–73 °C. The juice is then heated to 80 °C–90 °C in purification section for liming and carbonation processes to remove non-sugars.

After purification the cleaned juice, which in the sugar industry is called "thin juice" having about 15 w% sugar is then heated in a series of heaters to raise its temperature to boiling points or a little higher prior to feed to evaporator.

The juice is then concentrated in multiple-effect evaporators to 65–72 w%. The concentrated juice is then crystallized and separated through centrifugation and dried for packing.

3. New multistage pressure-driven membrane concentration process

Pressure-driven membrane processes like reverse osmosis are not generally able to achieve a concentration as high as when using evaporation. Osmotic pressure, viscosity and solubility set the upper limit of the concentration through reverse osmosis [17].

The osmotic pressure is a function of concentration and temperature. Fig. 2 illustrates the effect of concentration and temperature on osmotic pressure and dynamic viscosity. For aqueous sucrose solution the osmotic pressure and viscosity increases exponentially with concentration. The classical reverse osmosis concentration processes are economically limited to concentrations between 25 and 30 w% as a pre-concentration step. The osmotic pressure of 30 w% sucrose solution at 80 °C is about 42 bar. This requires an operating pressure up to 50 bar. Above this pressure for this concentration the cost is not justified by energy savings.

The osmotic pressure and viscosity are the functions of temperature also. The osmotic pressure increases almost linearly with temperature while the viscosity decreases exponentially. The effect of temperature on viscosity is very prominent because the viscosity at 50 w% concentration decreases almost 6 times, i.e. from 12 mPa.s at 25 °C to 2.3 mPa.s at 80 °C. This very large decrease in

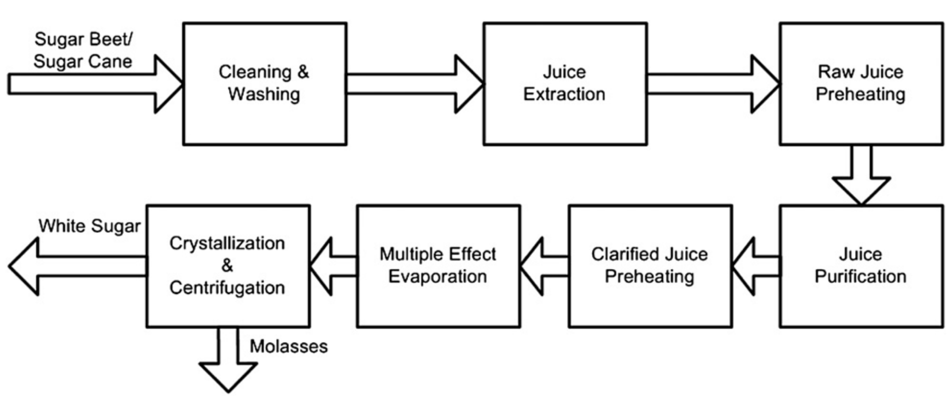

Fig. 1. Simplified flow sheet diagram of conventional sugar manufacturing process.

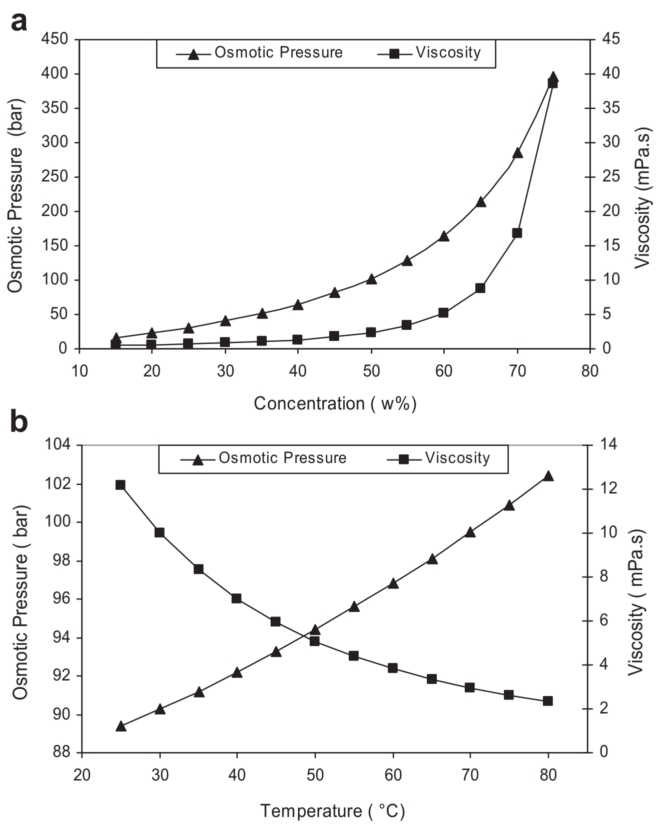

Fig. 2. a) Effect of sucrose concentration on osmotic pressure and dynamic viscosity at 80 °C. b) Effect of temperature on osmotic pressure and dynamic viscosity at 50 w%.

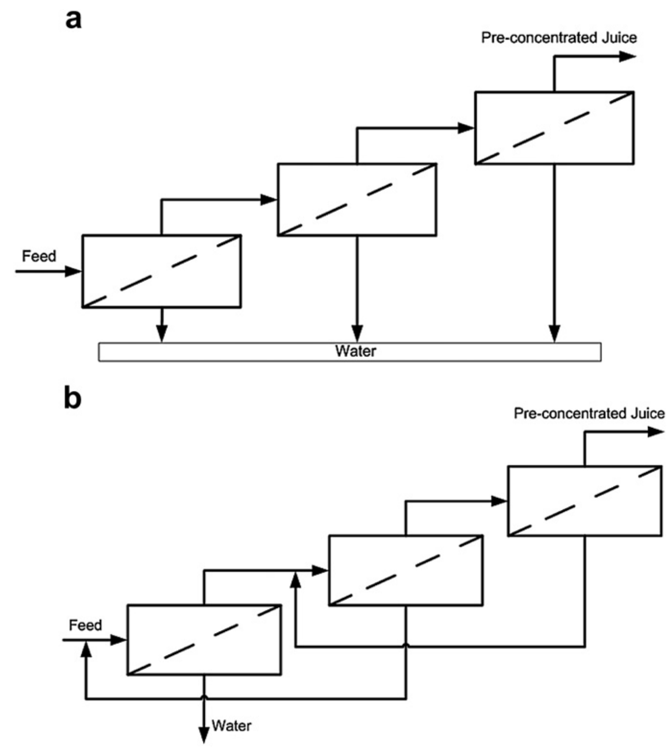

Fig. 3. a) Classical multistage pre-concentration process. b) Novel multistage pre-concentration process.

viscosity is very good for the hydrodynamics of the solution in the membrane module and will increase the mass transfer coefficient and decrease the pressure drop across the membrane element.

The osmotic pressure of sucrose solution at 80 °C and 50 w% is 100.2 bar. This requires more than 110 bar of pressure to pass through RO membrane in the classical pre-concentration process. The new multistage pressure-driven membrane concentration processes is capable to concentrate sugar solutions up to 45–50 w % at 80 °C and moderate operating pressure of 32 bar by using RO and NF membranes with different rejections and recycle streams. The process has been shown in Fig. 3. The operating pressure of 32 bar is well below the osmotic pressure of 102 bar of the concentrated product solution at 80 °C. Higher concentration at moderate applied pressure has the advantage of low capital and operating cost.

4. Energy consumption of pre-heating and concentration processes

After clarification, beet thin juice is typically available at about 80 °C before evaporation.

It is common to heat the juice to or above the boiling point in a heater ahead of the evaporators, since this is generally considered to be cost-effective in respect of evaporator capacity. If the juice entering the first effect of evaporators is below the boiling point, part of the heating surface in the evaporator has to be used to heat up the feed to this temperature. This is an inefficient use of the heating surface, and adversely affects the rate of evaporation [18]. In beet sugar factories, the juice entering the evaporator is thermostable and can be heated nowadays to 125–135 °C [19].

For pre-heating the beet thin clarified juice, bleed vapour from the different evaporator effects are used for steam economy. Energy consumption and savings calculations for thin juice concentration are based on concentrating the thin sugar juice from an initial concentration of 15 w% at 129 °C to a final concentration of 70 w% with steam at 145 °C. The values of steam and feed (used in the calculations) to the first effect of evaporator are real values of a beet sugar factory in the Europe.

4.1. Energy savings of thin juice pre-heating

In conventional processes all the clarified thin juice will pass through the heat exchangers while in membrane integrated processes, only the product (retentate) from the membrane process will pass through heat exchangers. As the membrane process will concentrate the juice at about 80 °C and will remove about 82% of water from the feed which is about 70% of the total feed. Therefore, the feed to the heat exchangers will be reduced by 70%. Consequently this will reduce the energy consumption and heat transfer area requirements of thin juice pre-heaters by up to 70%. The thin juice is normally heated by the bled vapours from the different effects of a MEE. Therefore, the vapour bleeding from evaporator for thin juice pre-heating will also be reduced by 70%. Furthermore as only 30% of the juice will be heated to a higher temperature therefore the risk of thermal degradation and colour formation will be decreased significantly which will also increase the efficiency of crystallization process.

4.2. Energy consumption of multiple-effect evaporator

The amount of water to be removed by evaporation in a beet sugar factory is about 95%. Typically, 75% of beet is water and about 20% water is added during the production processes [16]. Evaporating this very large proportion of water consumes enormous amounts of energy due to high latent heat of water.

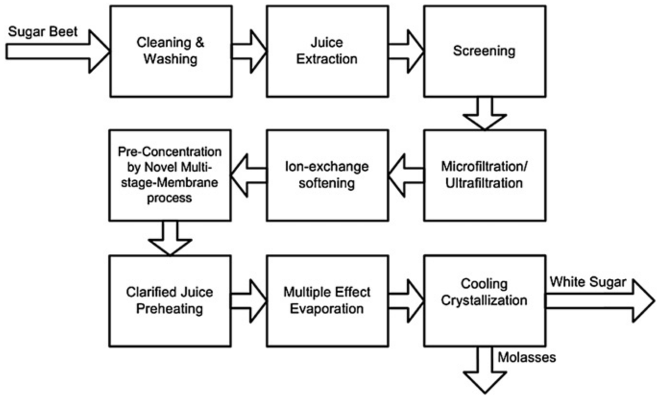

Fig. 4. Simplified flow sheet of the proposed novel sugar manufacturing process.

Theoretically single effect evaporation uses 1 kg of steam to evaporate 1 kg of water. In multiple-effect evaporation, 1 kg steam entering the first effect can evaporate as many kilograms of water as there are effects in the evaporator. In multiple-effect evaporators the vapour produced in the first effect is used as a heating medium in the second effect and so on. The amount of water to be evaporated in the evaporation can be calculated by Eq. (1),

$$m_{\mathrm{w,evp}} = m_{\mathrm{j,in}}\left(1 - \frac{\mathrm{DS_{j,in}}}{\mathrm{DS_{j,out}}}\right) \tag{1}$$

In the absence of vapour bleed, the amount of steam needed in multiple-effect evaporation can be calculated by dividing the total amount of water to be evaporated by the total number of effects. For example, for 100 kg water to be evaporated in a 5-effect evaporator, 20 kg of steam will be required to feed in the first effect. The minimum energy required for evaporation can be calculated by the Eq. (2),

$$Q_{\mathrm{EVp}} = \frac{\lambda_{\mathrm{s}} \cdot m_{\mathrm{w,evp}}}{N_{\mathrm{T,eff}}} \tag{2}$$

Where Q_{EV}, is the thermal power (kW) and $N_{\mathrm{T,eff}}$, is the total number of effects in evaporator and λ_{s} is the latent heat of evaporation (kJ/kg).

Eq. (2) calculates the minimum theoretical energy requirements for MEE without vapour bleedings but in sugar factories vapours are withdrawn from the different effects of MEE as low pressure steam for different heat users like raw juice purification, clarified juice pre-heating and crystallization sections. If membranes remove most of the water then less vapour will be available for bleeding and the demand of these heat consumers will be fulfilled by exhaust steam. This point must be taken into consideration, although the use of bleed vapours saves energy but this is not totally free of cost. For example the exhaust steam requirements to the first stage of MEE will be increased if vapours are withdrawn from the MEE for other heat consumers. In a typical example for a six-effect evaporator 0.17 kg steam is required to evaporate 1 kg water but if vapours are withdrawn for other heat users the steam requirements increases to 0.3 kg steam per kg water evaporated.

Additionally, the membrane process concentrating the juice to 50 w% will reduce the feed to the evaporator by 70%. Consequently the vapours needed for pre-heating will also decrease by 70% and the novel process is still able to provide vapours for the remaining 30% feed for pre-heating. Furthermore, G. Vaccari et al. [20] presented a sugar manufacturing process (from beet) in which raw juice is purified by microfiltration and softened with an ion-exchange process while for crystallization they proposed cooling crystallization (although the process has never been applied on industrial scale). This process has almost eliminated the need of vapour bleeding. Consequently, the proposed novel multistage pre-concentration process will work very well in combination with such a pre-treatment process and will reduce the exhaust steam consumption significantly. The proposed novel sugar membrane-based pre-concentration process in combination with the suggested process of [20] is presented by a simplified flow sheet in Fig. 4.

4.3. Energy consumption of pressure-driven membrane processes

Reverse osmosis uses pressure to concentrate a solution by forcing water through a semi permeable membrane, which allows the water to pass through but prevent the passage of solutes. The pressure produced by the high pressure pump must overcome the osmotic pressure of the solution at the membrane surface.

The high pressure pump is the main energy consuming component of the reverse osmosis processes to remove water from the solution. The theoretical amount of energy required to separate

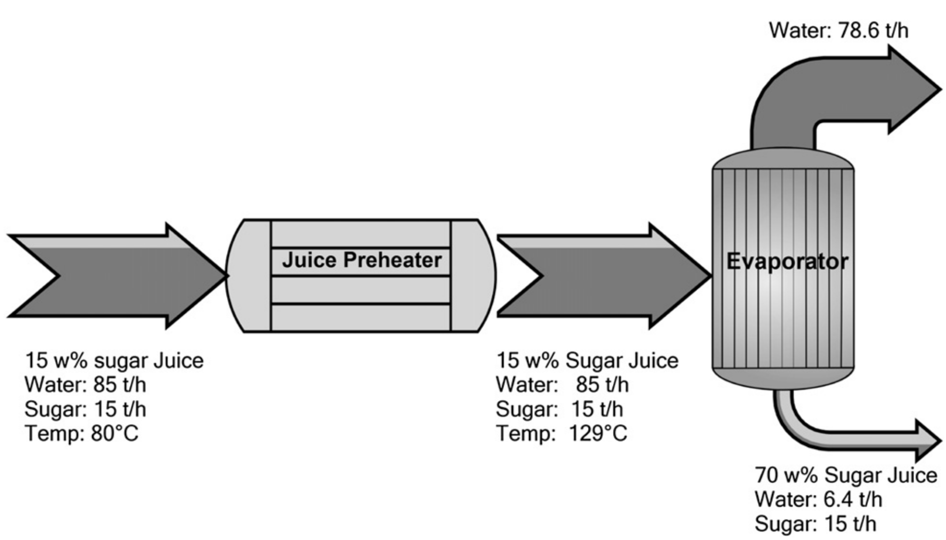

Fig. 5. Conventional clarified thin sugar juice pre-heating and concentration process.

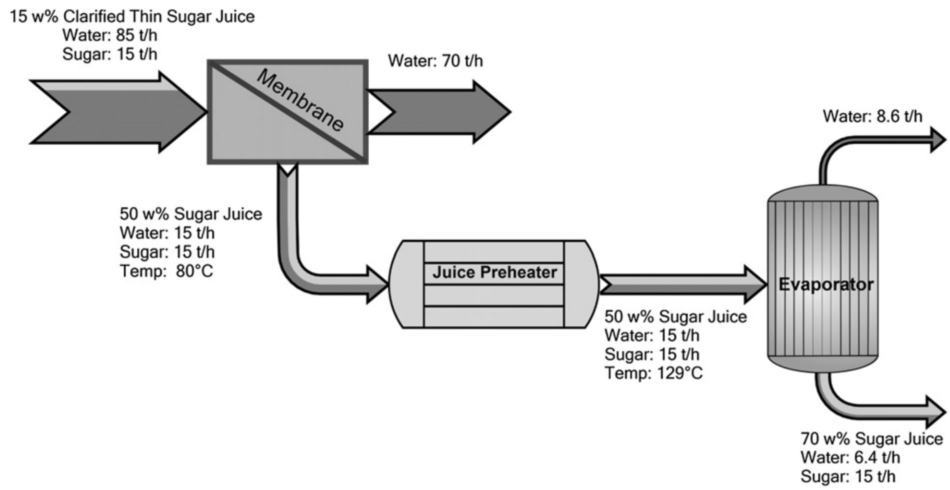

Fig. 6. Integrated novel Membrane-thermal clarified thin sugar juice pre-heating and concentration process.

water from a solution by reverse osmosis is the volume moved times the pressure used to move it:

$$E_{\mathrm{p}} = \frac{q_{\mathrm{j}}\Delta P}{\eta_{\mathrm{pump}}} \tag{3}$$

Where E_{p},is the pump power (W), q_{j} is the flow rate ($\mathrm{m^3/s}$), ΔP is the transmembrane pressure (Pa) and η_{pump} is the efficiency of the pump. The efficiency of a high pressure piston pump is generally between 0.5 and 0.9. Here we have assumed a pump efficiency of 0.7.

5. Energy consumption comparison of membrane and evaporation

A joule of energy in the form of heat and a joule of energy in the form of electricity are not equally valuable. Typically, thermal electric power plants have energy conversion efficiencies around 40%. Therefore electricity that comes out of a power plant is clearly more valuable than the thermal energy that goes in [21]. The main energy consuming component of a pressure-driven membrane process is the high pressure pump which uses electrical energy while evaporation uses thermal energy to evaporate water from solutions. The net advantage may be estimated using the method of the substitution coefficient commonly used in membrane processes evaluations [22]. This coefficient compares the primary energy saved to the electrical energy consumed in cycles that utilizes electricity-consuming operations in substitution of conventional thermal operations. The substitution coefficient is defined by the ratio of the primary energy (thermal) saved in the new process with respect to the conventional processes and the amount of electrical energy consumed, relative to the conventional processes:

$$\mathrm{CS} = \frac{C_1 - C_2}{E_2 - E_1} \tag{4}$$

Table 1
Energy consumption comparison and saving for 100 t/h feed of thin sugar juice for 5-effect evaporator and pressure-driven membrane from 15 w% to 70 w%.

Process	Energy consumption kW	Energy savings relative to MEE,%
MEE	9296	
Membrane + MEE	503 + 996	**84**
Membrane + conversion losses for electrical energy (34.3% efficiency) + MEE	503 + 963+996	**73.5**

Where CS is the substitution coefficient, C is the consumption of thermal primary energy (MJ or Mcal), E the consumption of electrical energy (kWh), 1 and 2 the relative index of the conventional and innovating processes, respectively. Taking into account that 1 kWh of electrical energy requires a power plant to burn about 10.5 MJ of primary energy from a combustible source (oil, gas, coal etc.), the substitution is acceptable when the CS value is greater than 10.5 $\mathrm{MJ_{prim}/kWh_{el}}$ (2.5 Mcal/kWh).

The conventional and proposed new integrated pre-heating and concentration processes are shown in Figs. 5 and 6.

In the present work multistage pressure-driven membrane processes have been used in combination with a 5-effect evaporator for the concentration of clarified thin sugar juice. Table 1 shows the energy consumption of conventional and membrane-based concentration processes. The integration of a multistage pressure-driven membrane process with a MEE reduced the direct energy consumption of the sugar juice concentration process by about 84%.

Considering the substitution coefficient CS of 59.4 MJ/kWh for this process, substantial primary energy savings can be achieved: Assuming a thermal power plant efficiency of 34.3% for the electrical energy, a reduction of primary energy consumption by 73.5% can be predicted, even at a conversion efficiency of as low as 12% a reduction of primary energy consumption of 54% can be reached.

Sugar plants where electricity demand is typically balanced with combined heat and power (CHP), a simple substitution coefficient in which reduced co-generation is not taken into account will not work. In this case a detailed analysis should be made to calculate the net primary energy savings.

6. Conclusions

In this work energy savings for evaporation and thin juice pre-heating in beet sugar industry have been presented. The savings are based on the application of a new multistage pressure-driven membrane technology for pre-concentration of thin sugar juice from initial feed concentration of 15 w% to 50 w% at moderate pressure of 32 bar and 80 °C. In a classical single stage pressure-driven membrane processes for thin sugar juice concentration of 50 w%, an operating pressure of more than 110 bar is necessary. This very high transmembrane pressure is not only uneconomical but at 80 °C it is not even possible to find operating conditions for the presently available polymeric membranes. The new process is capable to remove about 82 w% water from thin sugar juice, thus,

decreases the total amount of thin juice by 70 w%. As the membrane concentration takes place at 80 °C, which is the temperature where thin juice is available from previous processing. Therefore, only 30% of the thin juice will be heated to a temperature needed before evaporation which is normally in the range of 125 °C–130 °C. The heat for this is typically taken from MEE as bleeding vapour. Consequently vapour bleeding for pre-heating will be reduced by 70% and the novel process can provide bleed vapour for 70% less thin juice. This will reduce the energy consumption and heating area requirement of thin sugar juice pre-heating by about 70%.

The MEE, which is a very energy intensive process, have also to process only 30% of the total feed. This will not only decrease the size of evaporators by about 70% but will also reduce the energy consumption of the sugar juice concentration process by about 84%. Sugar solutions are unstable at higher temperatures and the colour formation increases with higher temperature which affects the crystallization process and the quality of the product. With this new process only 30% of the feed will be treated in MEE. Therefore, it will decrease residence time in the evaporator section the thermal degradation and colour formation. Consequently this will increase the efficiency of the crystallization step.

The application of the new process in the existing sugar industry will increase the capacity of the present evaporation stage without the addition of further evaporator area. An extension of power plant is not necessary because the new process is very energy efficient and will need less steam compared to the conventional concentration process.

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Nomenclature

Q_{EVp}: Evaporator duty (kW)
m_j: Juice flow rate (kg/s)
m_s: Steam flow rate (kg/s)
λ_s: Latent heat of evaporation (kJ/kg)
$m_{w,evp}$: Mass flow rate of water to be evaporated (kg/h)
$N_{T,eff}$: Total number of effects of evaporator
$m_{j,in}$: Mass of juice entering the evaporator
$DS_{j,in}$: Dry substance of juice entering to evaporator (w%)
$DS_{j,out}$: Dry substance of juice leaving the evaporator (w%)
ΔP: Transmembrane pressure (Pa)
q_j: Volumetric flow rate of juice passing through pump (m^3/s)
E_p: Energy consumption of high pressure pump (w)
CS: Substitution coefficient for primary energy saving (MJ/kWh)